Maintaining an FRC by two counter-rotating magnetic fields

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Introduction

A rotating magnetic field (RMF) can be used to both generate and maintain a field reversed configuration (FRC) [1,2]. However, if the particle confinement time is sufficiently large, the ion fluid eventually catches up with the electron fluid [3] with consequent loss of plasma current and equilibrium. Clemente [4] proposed the use of a second counter-RMF to control the ion motion for cases where the particle confinement time is sufficiently large for the effect of ion motion on the net current to be significant. The Clemente scheme would be most applicable for the following scenario:

1. A hot FRC is generated.
2. The FRC is translated to a separate chamber.
3. An RMF (referred to as the (-) RMF) is applied to maintain the plasma current (and hence the flux).
4. A second counter-RMF (referred to as the (+) RMF) is applied to entrain the ion fluid and prevent it being dragged by the electron fluid through momentum transfer collisions.

In the steady state the electron and ion fluids rotate synchronously with the (-) RMF and the (+) RMF respectively. Hugrass [5] has demonstrated the existence of the Clemente steady states where both RMFs penetrate much farther than the classical skin depth.

The Clemente steady states

In order for the electrons to remain entrained by the (-) RMF, the (+) RMF must exert a negligible torque to the entrained electron fluid. Similarly, in order for the ions to be entrained by the (+) RMF, the (-) RMF must exert a negligible torque to the entrained ion fluid. The possibility of achieving both conditions can be seen from the following analysis [6].

The steady part of the θ component of the force density due to each RMF on the electron fluid is given by:

$$F_e^{\pm} = \mp \frac{n m_e \omega^{\pm 2} r \varsigma_e^{\pm 2}}{2 S_e^{\pm} \xi^{\pm}} \Bigg/ \left[\left(\frac{1}{S_e^{\pm}} + \frac{m_e}{m_i} \frac{1}{S_i^{\pm}} \right)^2 + \frac{1}{\xi^{\pm 2}} \right] \tag{1}$$

where $\zeta_e^{\pm} = e|B_r^{\pm}|/\omega^{\pm} m_e$.

Similarly, the steady part of the θ component of the force density due to each RMF on the ion fluid is

$$F_i^{\pm} = \mp \frac{n m_i \omega^{\pm 2} r \varsigma_i^{\pm 2}}{2 S_i \xi^{\pm}} \Bigg/ \left[\left(\frac{1}{S_e^{\pm}} + \frac{m_e}{m_i} \frac{1}{S_i^{\pm}} \right)^2 + \frac{1}{\xi^{\pm 2}} \right] \tag{2}$$

The $\mp$ in equations (1 & 2) applies when $\omega^{-} > 0$ and $\omega^{+} < 0$ (and we take $\xi^{\pm} = \left|\frac{\nu_{ei}}{\omega^{\pm}}\right|$). $S_e^{\pm}$ and $S_i^{\pm}$ are the electron and ion slips with respect to each RMF.

The operating point for the electron fluid may be found by the intersection of the net force density from both RMFs and a *load line* representing the resistive force density due to collisions with the ion fluid. This represents a solution to the equation:

$$F_e^{-} + F_e^{+} = -F_{coll} = nm_e\nu_{ei}\omega^{+}r\left(S_i^{+} - S_e^{+}\right) \tag{3}$$

Figure 1 shows a typical set of curves showing the forces on the electron fluid for the case $\omega^{-} = 20\omega^{+}$. The electron fluid operating point under the (-) RMF alone is only marginally changed by the application of the (+) RMF. The electron fluid will thus maintain synchronous rotation with the (-) RMF.

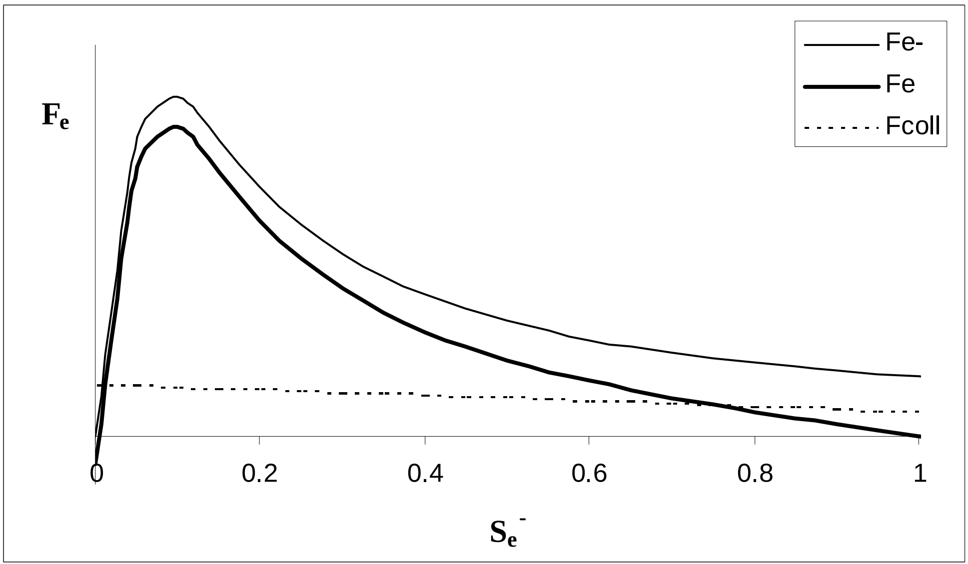

Figure 1: (i) The force density on the electron fluid due to the (–) RMF (F_e^{-}), (ii) the resultant force density (F_e), and (iii) a typical *load line* representing the collisional drag force; plotted against S_e^{-}. The vertical scale is in arbitrary units.

The operating points for the ion fluid may be similarly found. The net force density on the ion fluid due to the two RMFs is strongly peaked about $S_i^{+} = \xi^{+}\left(m_e/m_i\right)$, and has half peak width $\Delta S_i^{+} \cong 2\sqrt{3}\xi^{+}\left(m_e/m_i\right)$. Figure 2 shows the forces on the ion fluid and possible operating points for $m_e/m_i = 0.1$ since the details of the curves are difficult to display for the physical value of m_e/m_i. Operating point A corresponds to the steady state with the ion fluid rotating synchronously with the (+) RMF, and operating point C corresponds to synchronous rotation with the (-) RMF (operating point B is unstable, and does not correspond to a steady state solution). The existence of this operating point A is dependent on the magnitude of the RMF being sufficiently large. The actual steady state achieved depends on the initial conditions. This is usually a state corresponding to operating point C, except for a very small class of initial conditions which leads to the Clemente steady states (corresponding to operating point A)[6].

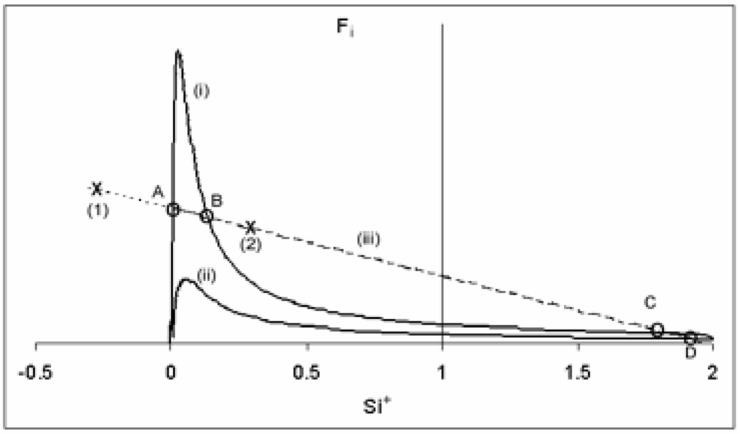

Figure 2: (i) The net force density on the ion fluid due to the (–) and (+) RMFs for the case $m_e/m_i = 0.1$, (ii) the same curve for a case where the magnitude of both RMFs is half the value for (i), and (iii) a typical *load line* representing the collisional drag force; plotted against S_i^+. Two possible initial points, (1) and (2) are shown. *A*, *B*, *C* and *D* represent possible operating points. The vertical scale is in arbitrary units.

Accessibility of the Clemente steady states.

We demonstrated the accessibility of the Clemete steady state from certain initial conditions in previous work [6 & 7]. The radial motion of the plasma was ignored in these studies. The Clemente steady states were accessible when the initial slip of the ions had a carefully prescribed radial profile [6]. The steady states were also accessible when the frequency of the (+) RMF was decreased at a rate greater than the ion relaxation rate due to collisions [7]. When the frequency of the (+) RMF is allowed to vary in such manner, there is no requirement for an initial profile for the slip of the ions. These results were demonstrated for the case $\omega^- = -\omega^+$. More recent work (to be published) showed that field penetration is more easily achieved if the electron fluid carries the majority of the current.
In this work we report simulations to study the accessibility of the Clemente steady states in a model which allows for the radial motion of the plasma to maintain radial equilibrium at all times. A preformed FRC is now considered, to which the (-) and (+) RMF's are applied. Access to the Clemente steady states is achieved for the following parameters.
$m_e/m_i = 5.45 \times 10^{-4}$, $B_\omega^- = B_\omega^+ = 20$ G, $\omega^+ = 0.1\omega^- = 1$ MHz, $R = 10$ cm, $T = 8$ keV,
$n_{max} = 8 \times 10^{18}$.

When only the (-) RMF is applied, the current decays with the ion relaxation time, eventually reaching a steady state where both electrons and ions rotate synchronously with the (-) RMF. When both RMFs are applied a true steady state is achieved, with the electrons and ions rotating synchronously with the (-) and (+) RMFs respectively (the (-) RMF is applied at t = 0, and (+) RMF applied after the electron fluid is entrained).

Penetration of the (+) RMF and capture of the ion fluid is enhanced when the electron fluid carries the majority of the current. This provides a broader force curve for the ion fluid, allowing a greater range of slip values for which the ion fluid may be captured, since the ions only relax slowly through collisions (on a much longer time scale than the diffusion of the (+) RMF). Also, if $\omega^+ < \omega^-$, there is no requirement that $\omega^+ > \nu_{ei}$ as stated in [6].

Further work is required on simulate the axial dynamics of the FRC. The application of two RMFs with frequency modulation may allow control of the length and radius of the FRC. This would be a very beneficial for any fusion reactor based on this technology.

[1] Jones I. R. Flinders University Report No. FUPH-R-151 (1979)
[2] Hoffman A. L., et al Nucl. Fusion 43 1091 (2003)
[3] Hugrass W. N. Aust J. Phys **37** 509 (1984)
[4] Clemente R. A., J. Phys. Soc. Japan, **67**, 3450 (1998)
[5] Hugrass W. N., Plasma Phys. Control. Fusion, **42** 1219 (2000)
[6] Visentin D. C., and Hugrass W. N., Plasma Phys. Control. Fusion, **45** 209 (2003)
[7] Visentin D. C., Plasma Phys. Control. Fusion, **45** 1027 (2003)